DIURNAL VARIATION IN STRATOSPHERIC TEMPERATURES AND HEIGHTS REPORTED BY THE U.S. WEATHER BUREAU OUTRIGGER RADIOSONDE

F. G. FINGER, R. B. MASON,[1] AND S. TEWELES

Stratospheric Meteorology Research Project, U.S. Weather Bureau, Washington, D.C.

ABSTRACT

The diurnal change in temperature and height measured by the new U.S. Weather Bureau outrigger radiosonde at and above 100 mb. has been determined from pairs of successive radiosonde observations taking place in daylight and darkness. Analyzed graphs of the change as a function of solar elevation angle are presented. For a given solar angle, the observed diurnal variations are found to be larger with afternoon daylight than with morning daylight. Furthermore, values computed for Plateau stations with afternoon daylight are particularly large.

Use of the white 50-mil rod thermistor with outrigger mounting has radically improved the compatibility of reported temperatures and heights at adjacent stations, primarily because the radiational temperature error has been reduced by a factor of about two to four. The observed diurnal variations measured by this new instrument are comparable with those of the military outrigger radiosonde, allowing for the slightly smaller thermistor of the latter.

1. INTRODUCTION

Among the difficulties encountered in the analysis of stratospheric constant pressure charts above the 100-mb. level have been the systematic differences of temperature and height reported at adjacent stations and at successive observations at a given station. The latter problem results mainly from the radiative error of the radiosonde thermistor which is particularly acute for the case when one observation is in daylight and the other in darkness. The incompatibility between reports at adjacent stations often can be traced not only to the use of different instrument types, but also arises where there is a significant difference of solar elevation between stations.

In an earlier paper, Teweles and Finger [1] discussed the day-night differences in temperature measured by the several different types of radiosondes employed by United States weather services during the IGY period [2]. Such differences for U.S. Weather Bureau internal-duct instruments averaged as much as 4°C. at 25 mb. and increased with altitude. These differences were evident even though solar radiation corrections were being applied to the observed temperatures. In contrast, the diurnal temperature differences observed with the United States military outrigger radiosonde do not exceed 2°C. at 25 mb. even without the application of a correction scheme.

Early in 1960 the U.S. Weather Bureau began a program to replace duct-type radiosonde instruments with an outrigger type. This instrument employs a white-coated rod thermistor of 50-mil diameter, somewhat larger than the 33-mil diameter of the rod used on the military radiosonde. By the end of 1960 most Weather Bureau stations had been equipped with the new radiosonde [3]. The data accumulated during this period permitted computation of the diurnal differences in the reported stratospheric temperatures and heights. The primary objective of this study is the presentation of graphs showing the day-night differences as a function of the daytime solar elevation angles.

2. DATA SELECTION

For this study the 0000 GMT and 1200 GMT rawinsonde observations from 30 stations were obtained for selected months within the period from June 1960 through May 1961. The eligibility of any station for selection for any given month depended upon: (a) the use of only the new outrigger-type instrument for all observations during the entire month; (b) a solar elevation angle of −5° or more at the time that the instrument passed through the selected constant-pressure surface at one of the two observation times, and complete darkness at the other time.

The latter requirement severely restricted the number of station-months available for processing. This is illustrated by the annual migration of the sunrise line in relation to the 1200 GMT observation (fig. 1a) and of the sunset line at the time of the 0000 GMT observation (fig. 1b). (The lines are representative of the 30-mb. level and thus correspond to a solar elevation of −5°.) At many stations, both observations intersect the 30-mb. level in daylight during some of the summer months and in darkness during the winter months. For example, in June the sunrise line at 1200 GMT (fig. 1a) is located over the eastern Pacific Ocean, and the 0000 GMT sunset

[1] Now with the Defense Communications Agency, Washington, D.C.

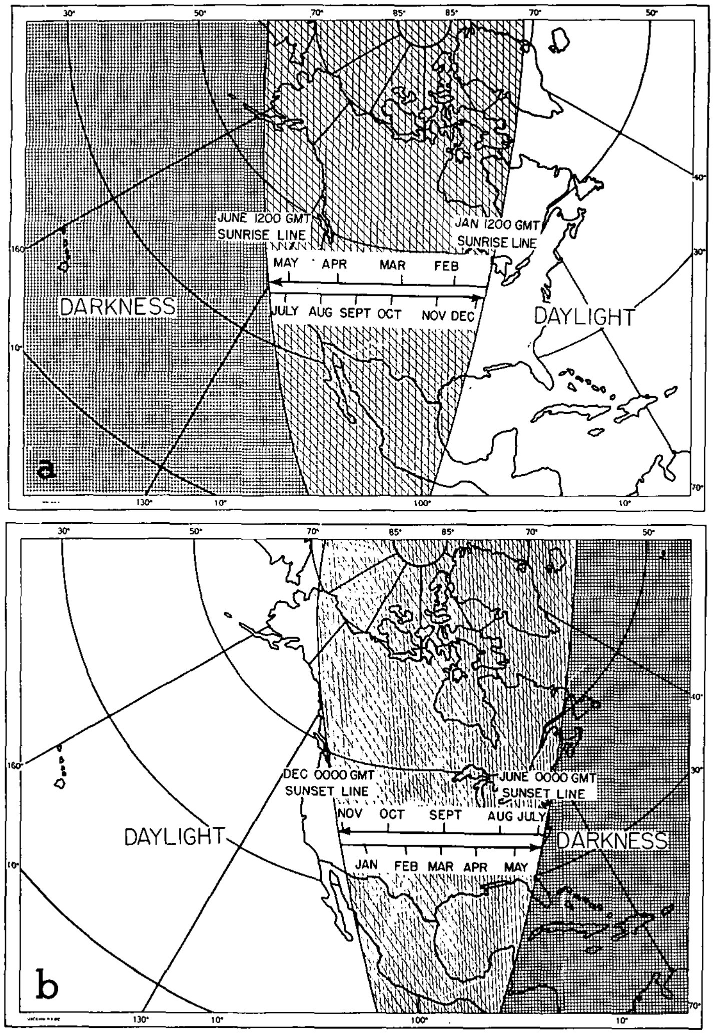

FIGURE 1.—(a) Yearly migration of 1200 GMT sunrise line at 30 mb. Direction of movement during period between extremes is shown by arrows. Position of line on the 15th day of each month is indicated by small line segments showing the general orientation of the line. (b) Yearly migration of 0000 GMT sunset line at 30 mb.

line (fig. 1b) can be found along the east coast of the United States. As a result at 30 mb. during this month, practically all 1200 GMT and 0000 GMT observations within the contiguous United States occur in daylight.

3. PROCESSING OF DATA

Data from punched cards provided by the National Weather Records Center were used to compute monthly means of day-night temperature and height differences,

$$\overline{\Delta T}=\frac{1}{n}\sum_{i=1}^{n}(T_s-T_d)_i \text{ and } \overline{\Delta H}=\frac{1}{n}\sum_{i=1}^{n}(H_s-H_d)_i$$

where T_s=temperature in sunlight with solar angle $-5°$ or more (solar radiation still reaches the 100- and 10-mb. levels when the solar elevation angle is $-4.1°$ and $-5.5°$, respectively), T_d=temperature in darkness (solar elevation less than about $-5°$), and n=the total number of individual day-night differences. H_s and H_d are heights with meanings analogous to those of T_s and T_d. Because of the decrease of available data with height at stratospheric levels, differences were computed for both the 12 hr. preceding and the 12 hr. following the times of T_s and H_s. To guard against the effects of possible gross errors within the punched card decks, the computer program discarded any individual ΔT or ΔH which varied from $\overline{\Delta T}$ or $\overline{\Delta H}$ by more than twice the standard deviation and then computed a new monthly mean. With the aid of an IBM 7090 computer, the calculations were carried out for data at 100, 50, 30, 25, 20, 15, and 10 mb.

Solar elevation angles for each station were based on three factors: (a) the time at which the daylight observation intersects each pressure level on the 15th day of each month; (b) an assumed balloon-ascent rate of 305 m. min.$^{-1}$; and (c) the relase time of the instruments, normally about 30 min. prior to the standard observation time. For cases of excessively variable time of release a monthly average solar angle was used.

4. DATA ANALYSIS AND DISCUSSION OF GRAPHS

As an initial phase of the analysis, graphs of $\overline{\Delta T}$ vs. solar elevation angle were plotted for each selected pressure level. Although it was possible to fit a single curve to each of these plots, the points did not appear to be normally distributed with respect to the resulting curve, particularly in the case of the $\overline{\Delta H}$ values. An investigation disclosed that the points representing $\overline{\Delta T}$ and $\overline{\Delta H}$ vs. solar angle could be separated into the following three classes:

(a) Morning daylight; observations from stations located in the eastern half of the United States and in the western Pacific Ocean. In this case the daylight observation occurs sometime between sunrise and noon.

(b) Afternoon daylight; observations from stations in the western United States, Alaska, and the eastern Pacific Ocean area. The daylight observation takes place between noon and sunset.

(c) Plateau stations; observations from stations located over the western United States at elevations exceeding 1100 m. The daylight observations at all these stations occur after noon.

The completed analysis of $\overline{\Delta T}$ and $\overline{\Delta H}$ vs. solar elevation angle for the three classes of data are shown in parts (a) and (b) of figures 2, 3, and 4. The temperature curves have been drawn as a best fit to the data and adjusted to conform to theoretical values of the true diurnal variation (Pressman [4]) at sunrise and sunset. To conserve space the curves for 30, 20 and 10 mb. are presented together in graphs without data points. At the higher levels, the data points show a decrease in number and increase in scatter. Nevertheless, the temperature curves fit the data in a reasonable fashion even at the 10-mb. level.

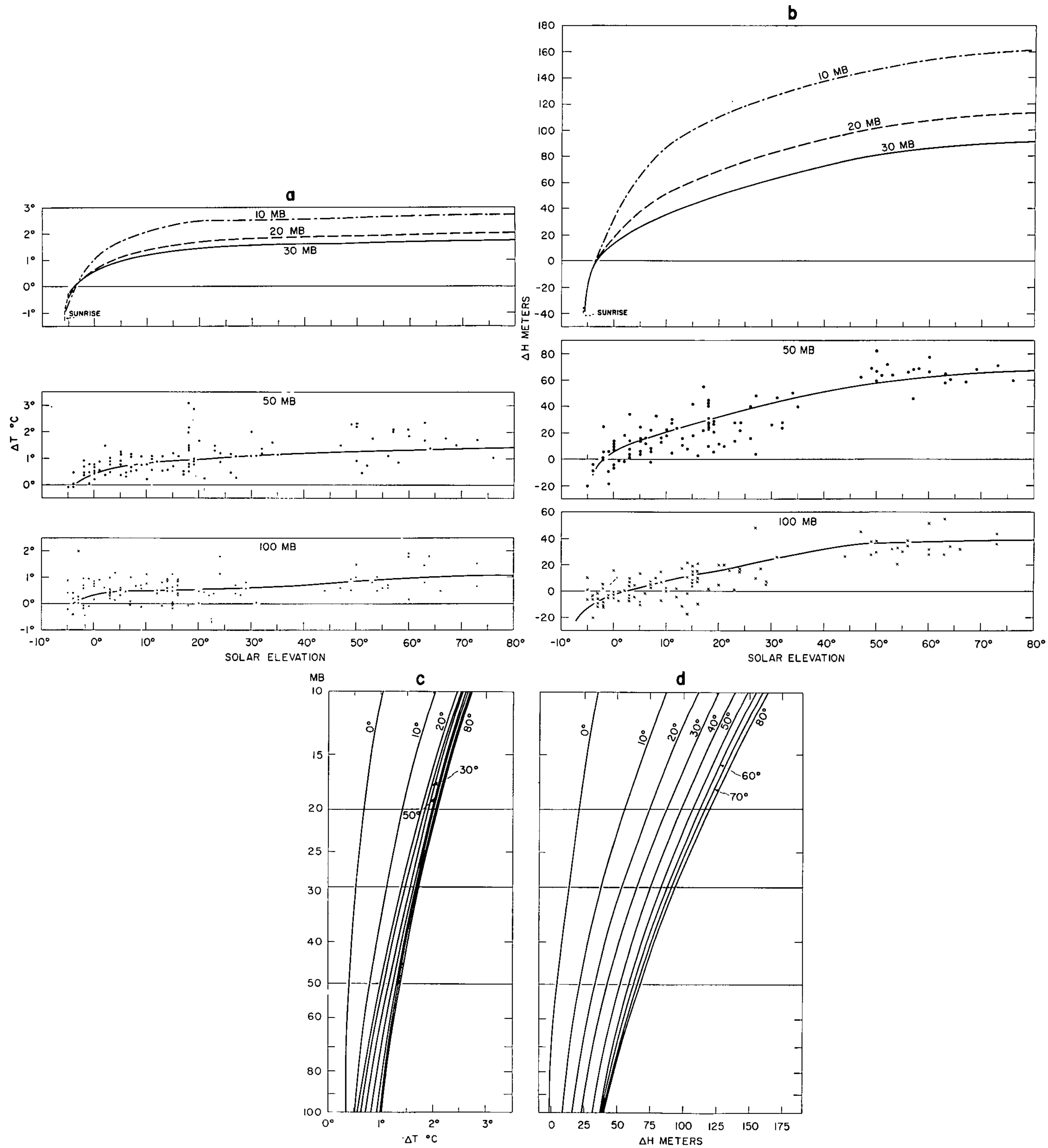

FIGURE 2.—Analyses of observed 12-hr. differences of temperatures and heights for morning-daylight stations using the Weather Bureau outrigger radiosonde: (a) $\overline{\Delta T}$ vs. solar elevation angle; (b) $\overline{\Delta H}$ vs. solar angle; (c) $\overline{\Delta T}$ at selected solar angles as a function of pressure; (d) $\overline{\Delta H}$ at selected solar angles as a function of pressure.

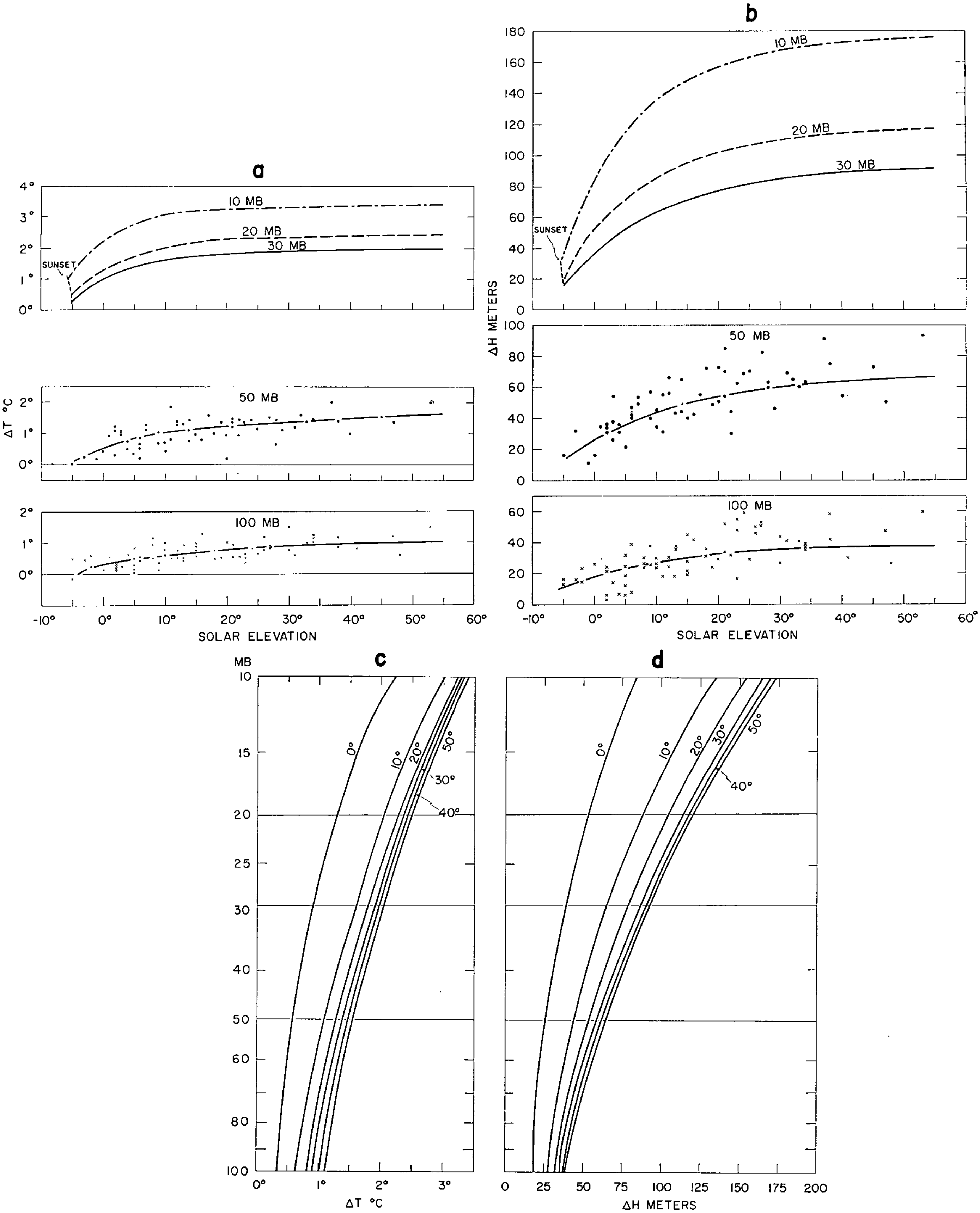

FIGURE 3.—Analyses of observed 12-hr. differences of temperatures and heights for afternoon-daylight stations using the Weather Bureau outrigger instrument. Explanation as in figure 2.

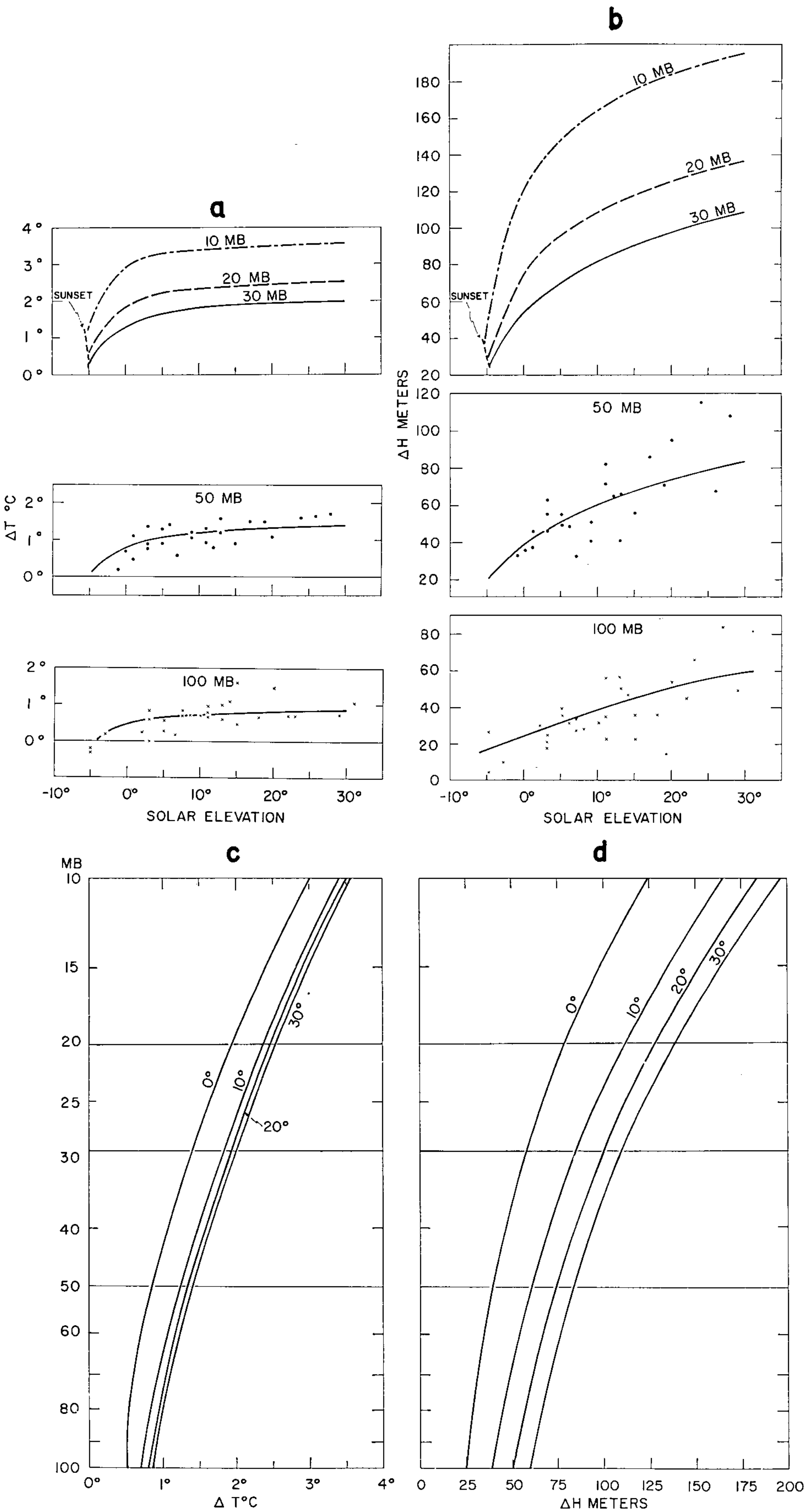

FIGURE 4.—Analyses of observed 12-hr. differences of temperatures and heights for Plateau area stations using the Weather Bureau outrigger radiosonde. Explanation as in figure 2.

TABLE 1.—*Values of* $\overline{\Delta T}$ *(top row) and* $\overline{\Delta H}$ *(bottom row) measured by Weather Bureau outrigger radiosonde for selected solar angles and pressure levels.* A*=afternoon-daylight stations,* P*=Plateau stations,* M*=morning-daylight stations (See text for description.) For comparison are listed values from the military outrigger instrument (MI) from* [1]

Solar angle	100 mb.				50 mb.				30 mb.			
	A	P	M	MI	A	P	M	MI	A	P	M	MI
−5°	−0.1	−0.2	−0.2	-----	0	0	−0.2	-----	0.3	0.4	−0.3	-----
	11	18	−14	-----	12	20	−14	-----	15	25	−16	-----
0°	0.3	0.5	0.4	0.1	0.6	0.8	0.4	0.3	0.9	1.4	0.5	-----
	18	25	−3	0	27	39	6	4	36	56	11	-----
10°	0.6	0.8	0.5	0.3	1.0	1.2	0.8	0.6	1.7	1.9	1.1	-----
	26	38	7	1	44	59	20	10	64	83	34	-----
20°	0.8	0.8	0.5	0.5	1.3	1.3	0.9	0.9	1.9	1.9	1.4	-----
	32	50	16	4	54	74	31	18	78	98	50	-----
30°	0.9	0.8	0.6	0.6	1.4	1.4	1.1	1.1	1.9	2.0	1.5	-----
	36	60	24	10	60	84	40	27	85	108	62	-----
40°	1.0	-----	0.7	0.8	1.5	-----	1.2	1.3	1.9	-----	1.6	-----
	36	-----	32	18	62	-----	50	38	88	-----	72	-----
50°	1.1	-----	0.9	0.9	1.6	-----	1.3	1.4	1.9	-----	1.6	-----
	38	-----	37	24	64	-----	58	47	92	-----	80	-----
60°	-----	-----	1.0	1.0	-----	-----	1.3	1.5	-----	-----	1.7	-----
	-----	-----	38	27	-----	-----	61	52	-----	-----	86	-----
70°	-----	-----	1.1	1.0	-----	-----	1.4	1.5	-----	-----	1.7	-----
	-----	-----	38	30	-----	-----	64	54	-----	-----	88	-----
80°	-----	-----	1 1	1.0	-----	-----	1.4	1.5	-----	-----	1.7	-----
	-----	-----	40	31	-----	-----	66	55	-----	-----	90	-----

Solar angle	25 mb.				20 mb.				15 mb.				10 mb.			
	A	P	M	MI	A	P	M	MI	A	P	M	MI	A	P	M	MI
−5°	0.4	0.5	−0.3	-----	0.5	0.6	−0.5	-----	0.7	0.9	−0.5	-----	1.1	1.3	−0.8	-----
	17	28	−18	-----	19	31	−20	-----	25	38	−20	-----	35	50	−20	-----
0°	1.0	1.6	0.6	0.5	1.3	1.9	0.6	-----	1.5	2.3	0.7	1.0	2.3	3.0	1.0	1.5
	45	64	17	10	53	75	17	-----	65	92	24	21	87	124	34	36
10°	1.8	2.0	1.2	1.0	2.0	2.3	1.4	-----	2.4	2.7	1.7	1.6	3.0	3.4	2.0	2.3
	72	94	40	26	86	109	50	-----	104	128	64	44	139	166	86	67
20°	2.0	2.1	1.5	1.3	2.3	2.4	1.7	-----	2.7	2.8	2.0	2.0	3.2	3.5	2.5	2.8
	88	110	56	40	102	125	68	-----	122	145	85	64	156	184	110	94
30°	2.1	2.2	1.5	1.5	2.3	2.5	1.8	-----	2.8	2.9	2.1	2.3	3.4	3.6	2.5	3.1
	95	127	70	54	109	137	82	-----	130	159	100	82	166	195	126	115
40°	2.1	-----	1.6	1.8	2.4	-----	1.8	-----	2.8	-----	2.2	2.5	3.4	-----	2.6	3.3
	100	-----	81	68	114	-----	93	-----	134	-----	111	98	170	-----	138	132
50°	2.2	-----	1.6	1.9	2.5	-----	1.9	-----	2.8	-----	2.2	2.7	3.4	-----	2.6	3.4
	102	-----	88	79	120	-----	103	-----	137	-----	119	110	175	-----	147	147
60°	-----	-----	1.7	1.9	-----	-----	2.0	-----	-----	-----	2.2	2.6	-----	-----	2.7	3.3
	-----	-----	94	85	-----	-----	108	-----	-----	-----	124	118	-----	-----	156	154
70°	-----	-----	1.7	1.8	-----	-----	2.0	-----	-----	-----	2.3	2.5	-----	-----	2.7	3.0
	-----	-----	98	88	-----	-----	114	-----	-----	-----	129	119	-----	-----	160	152
80°	-----	-----	1.7	1.5	-----	-----	2.0	-----	-----	-----	2.3	2.1	-----	-----	2.8	2.5
	-----	-----	104	86	-----	-----	116	-----	-----	-----	132	111	-----	-----	162	139

Height curves were derived from both the data and hydrostatic considerations; i.e., the height curve at each pressure level is the integrated result of the height curve at the next lower surface and a height difference in the intervening layer determined from the mean of the two temperature curves. A somewhat different representation of the analyzed data is shown in parts (c) and (d) of figures 2, 3, and 4. In these derived curves, $\overline{\Delta T}$ and $\overline{\Delta H}$ are represented as functions of solar angles and pressure. Included in table 1 are the values of $\overline{\Delta T}$ and $\overline{\Delta H}$ extracted from the curves for the three classes of data at each pressure surface.

Theoretical and observational studies suggest that only a portion of the observed diurnal variation of temperature and height can be ascribed to a true diurnal variation. From radiation theory, Pressman [4] concluded that the diurnal temperature wave at stratospheric levels has a minimum near sunrise, a value of zero at noon, and a maximum at sunset. The computed range of this true diurnal variation increases from only a few tenths of a degree Celsius at 20 km. to about 2°C. at 30 km. In a study employing observational data from Lajes, Azores, Harris et al. [5] found that the diurnal temperature variations calculated independently from wind-derived height changes in the stratosphere agreed in both phase and amplitude with those based on radiation theory.

To facilitate examination of the differences between the three classes of data, curves for 25-mb. $\overline{\Delta H}$ (fig. 5) have been derived from graph (d) of figures 2, 3, and 4 and the corresponding graph for the military instrument [1]. The greatest difference in magnitude between the morning and afternoon daylight curves appears at the lower solar angles. Unfortunately, the lack of data at very high solar angles has restricted the analysis of the afternoon daylight curve to below 50°. However, if the difference between this curve and that for morning daylight represents the true diurnal variation, the two curves should converge at the higher angles appropriate to the noon observation. The curves do show some tendency to converge in this manner.

There is no ready explanation for the larger diurnal variation observed at the Plateau stations. A suggested explanation is the combination of the true diurnal heating with exceptional heating of either instrument or atmosphere due to long-wave radiation emanating from the high terrain; that is, due to the exceptionally large diurnal heating of the ground surface on high plateaus in relatively cloudless regions. A contributing factor might be a diurnal variation in cloud cover, particularly the cirrus cloud cover. A daytime maximum cover would suppress the diurnal effect of solar radiation and vice versa.

For comparison, values of the observed diurnal variations measured by the military radiosonde [1] are also included in table 1 and figure 5. Although these curves were based on mixed data for both morning and afternoon daylight, the portions below a solar angle of about 50° are based primarily on morning-daylight stations. However, the relatively few afternoon-daylight data points at the lower solar angles deviated systematically from the analyzed curves, and therefore are plotted individually in figure 5. The position of these data points with respect to the curve for the military radiosonde suggests that the latter reacts to afternoon and morning daylight in the same manner as the Weather Bureau radiosonde.

To show the distribution of the observed 12-hr. differences, the monthly means of 25-mb. temperatures and heights at selected stations were found separately for 0000 GMT and 1200 GMT of March 1961. The difference between the values for these two times is plotted in figure 6. In March, over the eastern United States, the 1200 GMT observation intersects the 25-mb. level during the early morning daylight hours while the observation 12 hr. later takes place in darkness. Over the western section of the country, however, a reverse situation occurs, with late afternoon sunlight incident on the 0000 GMT observation.

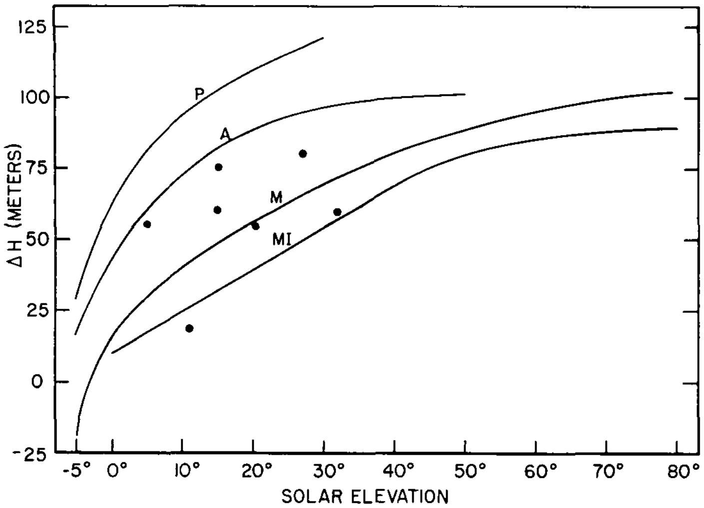

FIGURE 5.—Analyzed curves of Weather Bureau oturigger radiosonde $\overline{\Delta H}$ values at 25 mb. for: Plateau stations (P), afternoon-daylight stations (A), and morning-daylight stations (M). Curve of $\overline{\Delta H}$ values for the U.S. military outrigger instrument (MI), and afternoon-daylight $\overline{\Delta H}$ points (dots) are also shown (from Teweles and Finger [1]).

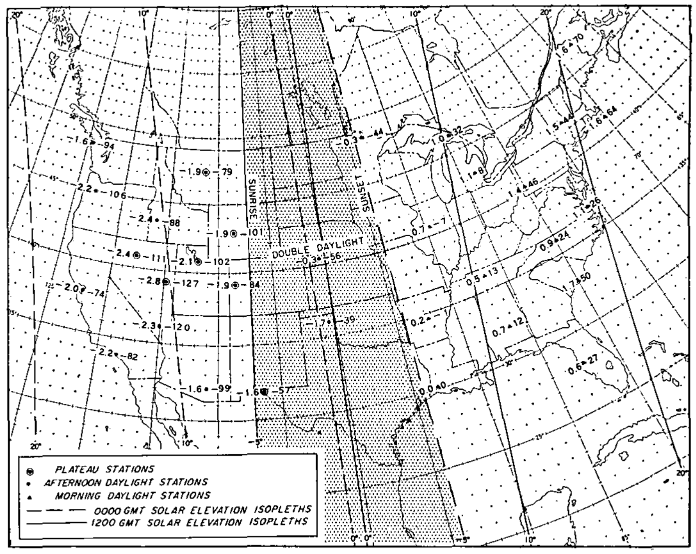

FIGURE 6.—$\overline{\Delta T}$ values in °C. (left of station symbols) and $\overline{\Delta H}$ values in meters (right of station symbols) at 25 mb. for selected stations using the Weather Bureau outrigger radiosonde during March 1961.

Over the Great Plains States, both observations take place within a period of daylight with low solar angles. The reversal in sign of the differences over the extreme western and eastern sections of the United States is evident. Negative signs extend eastward into the region of double daylight and even penetrate a short distance eastward into the area of morning sunlight.

This representation (fig. 6) illustrates the problem facing the analyst as he carries his contours and isotherms across the sunrise-sunset line or makes comparisons between maps at 12-hr. intervals. Of special interest is the area of large differences centered over the Great Basin. In contrast, over the eastern United States, the values show a regular increase eastward in the direction of higher solar angles for the daylight observation.

The negative signs in the region of double daylight agree with those that would be produced by the true diurnal temperature change with its maximum at sunset and its minimum at sunrise. However, the magnitude of the height differences in this region is too large to be explained in this manner. The explanation probably lies in the integrated effect of temperature errors in the lower portion of the 0000 GMT observation during which the instrument was in daylight.

5. APPLICATION OF THE GRAPHS

The numerical values extracted from graphs (c) and (d) of figures 2, 3, and 4, when subtracted from daytime observations, reduce all data to a common nighttime base. This method of correction may be applied by the analyst to data now being received by teletypewriter. The corrections could also be applied to observed temperatures *prior to their* use in hydrostatic computation of pressure-heights. The heights computed from such corrected temperatures would then require no further correction. This method is well-suited to automatic data processing (ADP) by electronic computer. A portion of this ADP procedure consists of a recomputation of transmitted data as a preliminary step to the computer-analysis of constant pressure charts. The introduction of information of the type contained in graphs (c) of figures 2, 3, and 4 into the ADP computer program insures the production of stratospheric charts undistorted by radiational errors.

Obviously, the application of the correction scheme outlined above can be subject to large uncertainties if the radiosonde involved does not measure pressure accurately. In such cases, the temperature ascribed to a given pressure level may have been measured at a somewhat different level. This type of error increases with the size of the correction, and its effects are now greatly reduced since the initial radiation error of the new outrigger radiosonde is only about one-half to one-fourth that of the duct-type instrument. The radiation error is further diminished as the pressure error decreases; thus the recent introduction of the highly accurate hypsometer pressure element is a desirable aid to accurate stratospheric map analysis.

6. CONCLUSIONS

The incompatibility between day and night soundings at stratospheric levels over U.S. Weather Bureau radiosonde stations has been effectively reduced by the introduction of an outrigger-type instrument to replace the several different duct types formerly in use. The employment of this new instrument has also reduced the incompatibility between soundings at adjacent stations since it is similar to the military-type instrument still used at a few stations.

The incompatibility of soundings taken on opposite sides of the sunrise or sunset lines also has been reduced, but not adequately for the purposes of synoptic analysis at 30 mb. or higher levels. This problem is particularly pronounced at the high Plateau stations of the western United States. To explain this "Plateau" effect, it is suggested that at stratospheric levels the instrument is directly affected by long-wave radiation emanating from the Plateau which normally exhibits a large diurnal variation in surface temperature.

The diagrams presented in this paper give the average day-night temperature and height differences for three different regions as a function of pressure and solar angle. The values given, when used as a correction for reducing temperatures and heights to the level of the nighttime observations, produce a compatible field of values greatly improving the accuracy of contour and isotherm patterns at stratospheric levels.

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